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FACULTY OF SCIENCE

Nucleosynthesis in AGB stars traced by isotopic ratios

Rutger DE NUTTE

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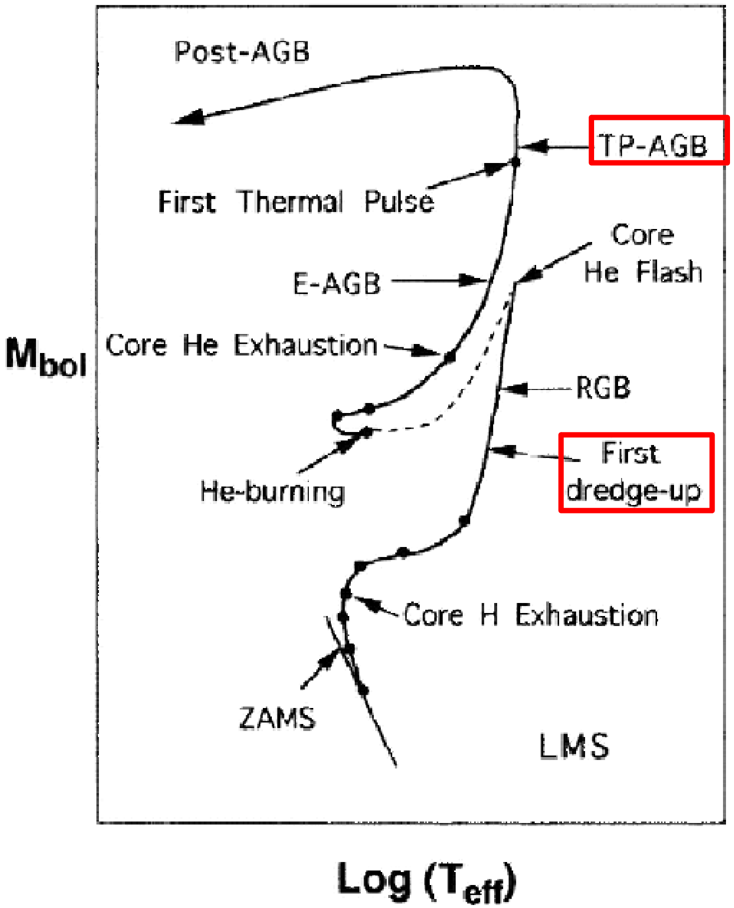
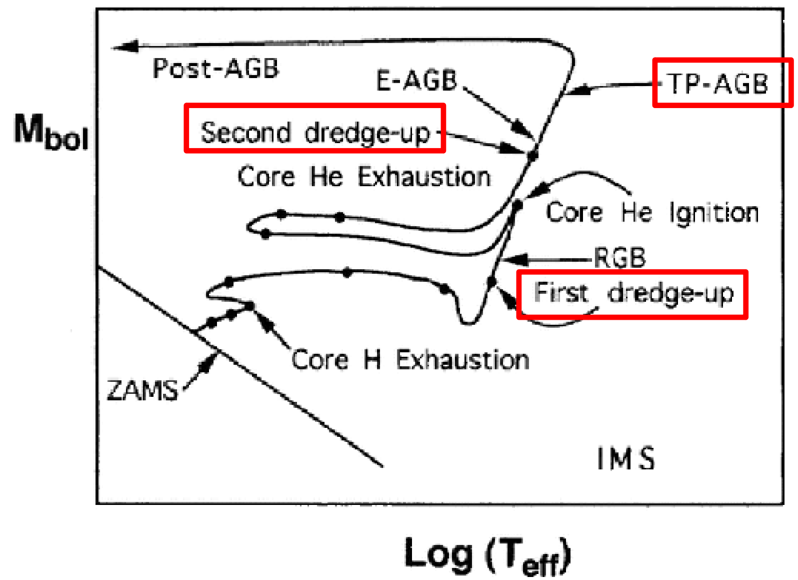
Introduction

Oxygen rare isotopes as tracers

Dredge-up (DU) events



$1M_{\odot}$

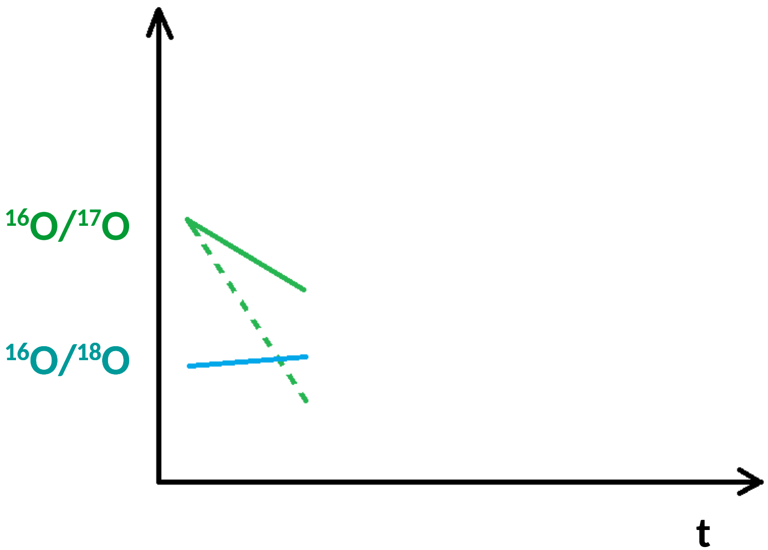


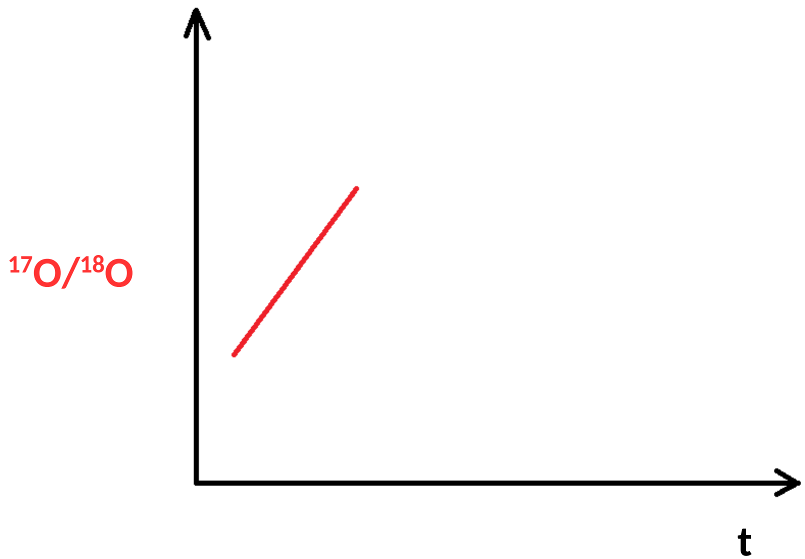
$5M_{\odot}$

Busso et al. 1999,
ARA&A 37, 239

Dredge-up (DU) events: FDU

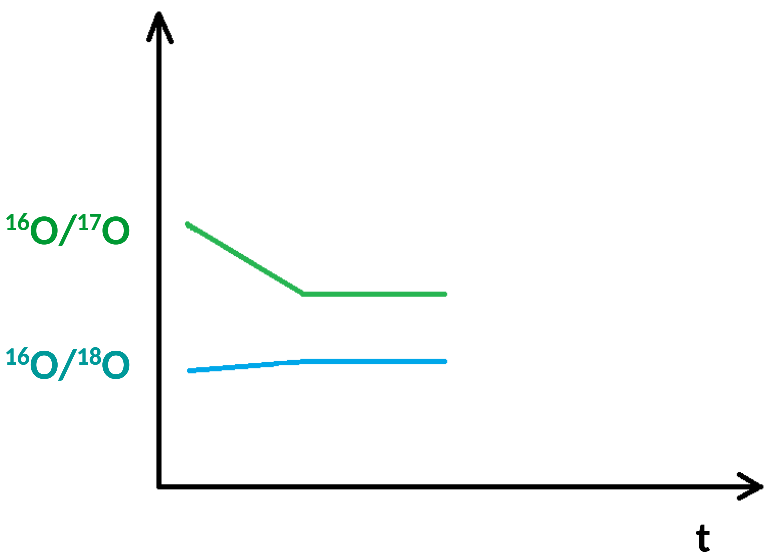
- During first red giant branch ascend
- Convective envelope penetrates partial H-burning shell
- RESULT (surface composition):

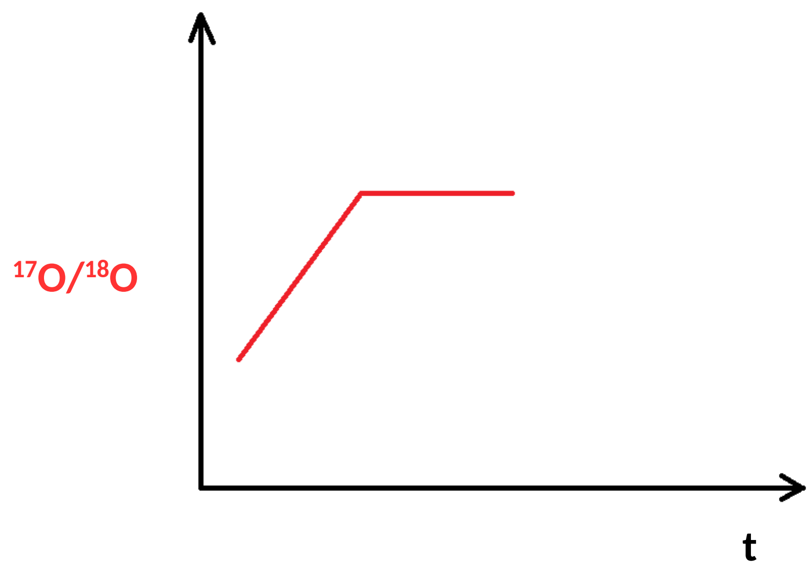




Dredge-up (DU) events: SDU

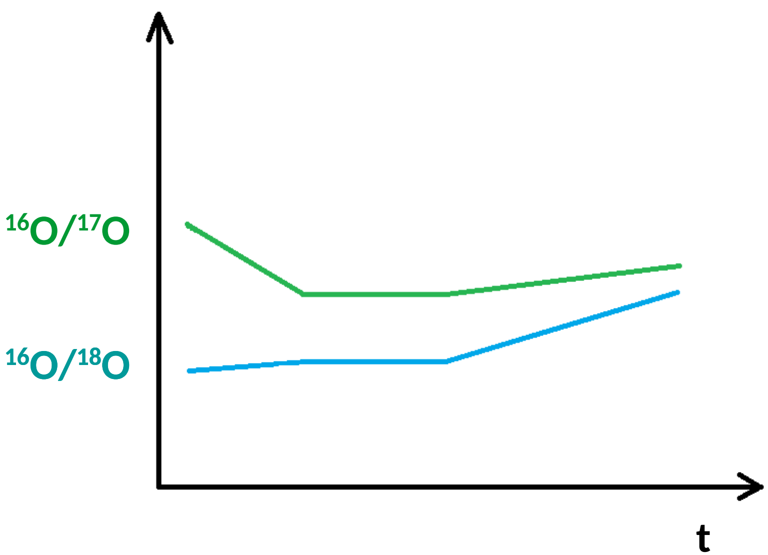
- For $M_* > 4\text{-}5M_\odot$ (dependent on composition)
- During formation of degenerate CO core
- RESULT (surface composition):

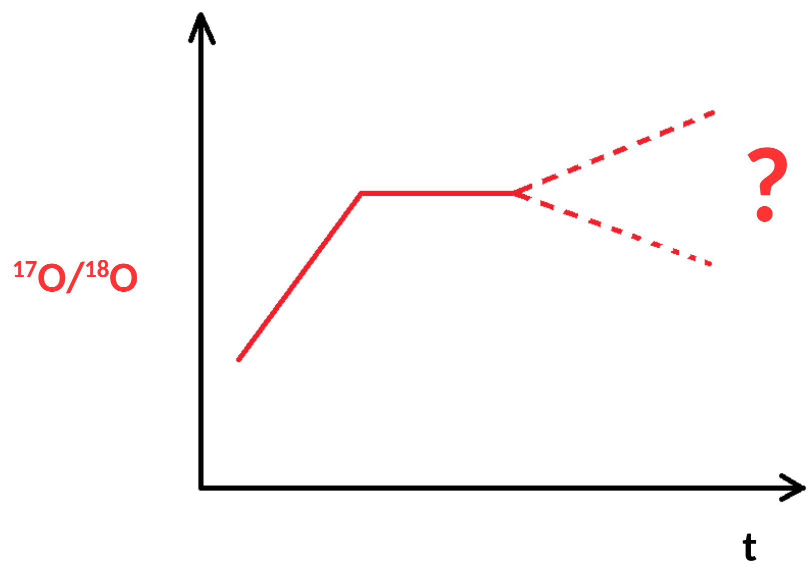




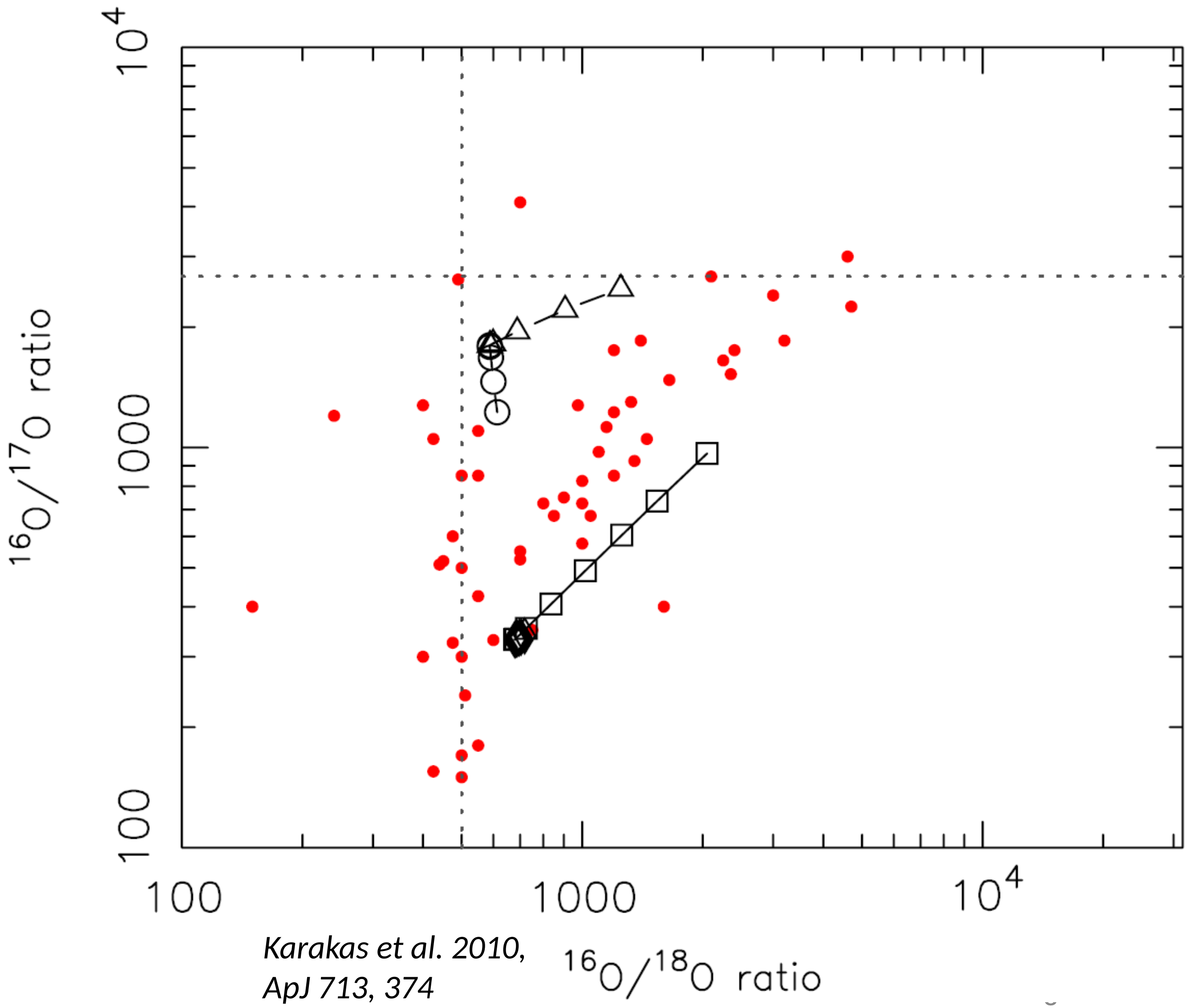
Dredge-up (DU) events: TDU

- Following He shell flash ($1M_\odot < M_* < 4M_\odot$)
- M (C/O<1) → C (C/O>1)
- Multiple cycles (thermal pulses TP's): 10^3 – 10^5 yr
- RESULT (surface composition):





Extra mixing?



Karakas et al. 2010,
ApJ 713, 374

Extra mixing?

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  (e.g. Karakas et al. 2010, Busso et al. 2010, Charbonnel & Lagarde 2010, etc.)

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- Possibilities:
  - Rotational mixing
  - Thermohaline mixing
  - Gravity waves
  - Magnetic buoyancy

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} Predict different isotopic ratios, testable from observations
! O-isotopes !

Observational selection effects

Observations of the extended circumstellar envelope (CSE)

Observations

- Study effect of nucleosynthesis and Dus (+extra mixing) by means of isotopic ratios

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  -> Possibilities:
  - **Interstellar gas measurements**
    (e.g. Wannier et al. 1976, Penzias 1981, etc.)

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- Study effect of nucleosynthesis and DUs by means of isotopic ratios
  -> Possibilities:
  - **Interstellar gas measurements**:
    Molded by generations of stars of various types
    (⇒ no relevance to single star evolution models, measured $^{17}O/^{18}O$ values very constant ~5x smaller than those already obtained in AGB CSEs
    e.g. Penzias 1981)

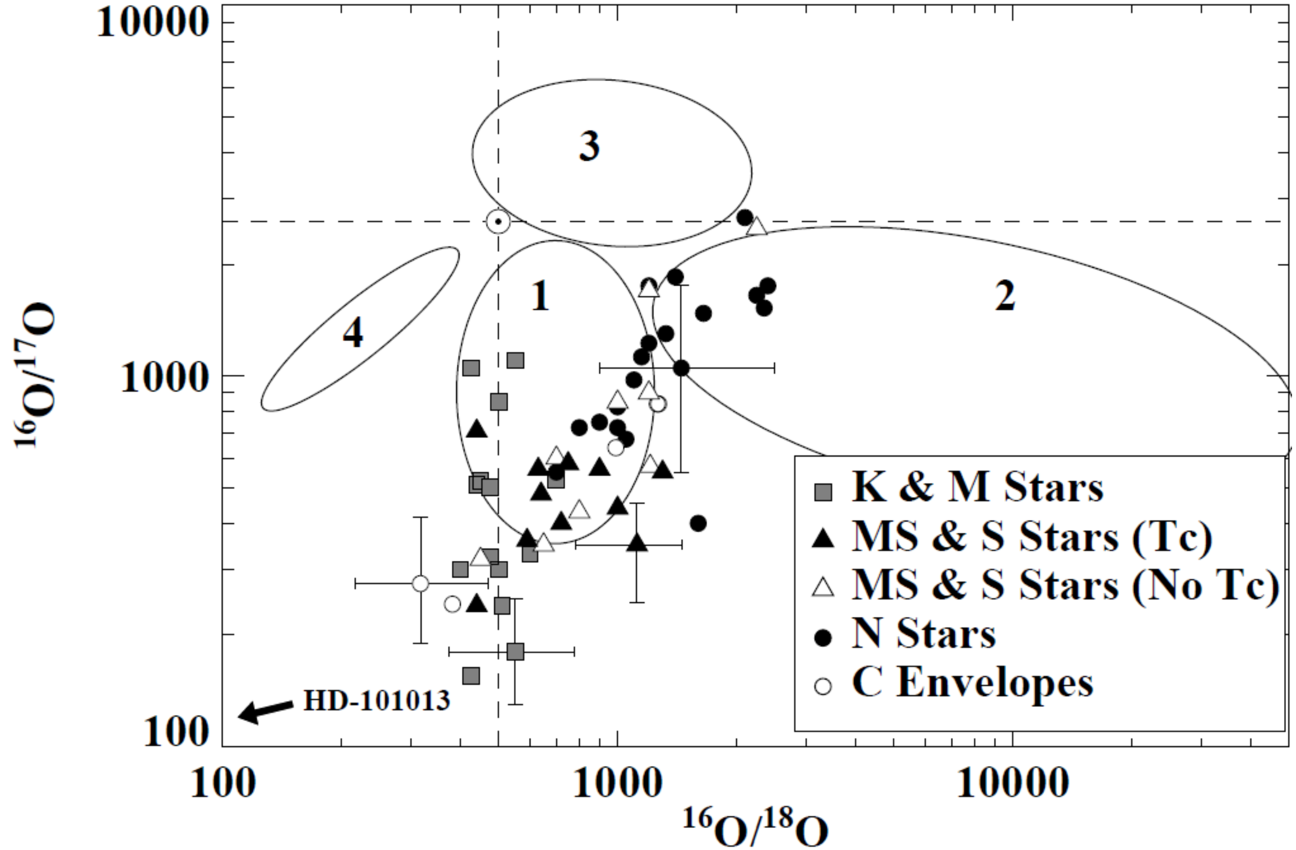
Observations

- Study effect of nucleosynthesis and DUs by means of isotopic ratios
  -> Possibilities:
  - ~~Interstellar gas measurements~~
  - **Presolar grains**
    (e.g. Nittler et al. 1997, etc.)

Observations

- Study effect of nucleosynthesis and DUs by means of isotopic ratios
  -> Possibilities:
  - ~~Interstellar gas measurements~~
  - **Presolar grains:**
    Thought to retain isotopic compositions of stellar gases from which they condensed
    BUT: also reflects complex interplay of galactic chemical evolution (spallation) **+** lab pollution
    + hard to differentiate origin of grain

Observations: presolar grains



Nittler et al. 1997,
ApJ 483, 475

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- Study effect of nucleosynthesis and DUs by means of isotopic ratios
  -> Possibilities:
  - ~~Interstellar gas measurements~~
  - (Presolar grains)
  - **Dense outer layers of stellar atmosphere**

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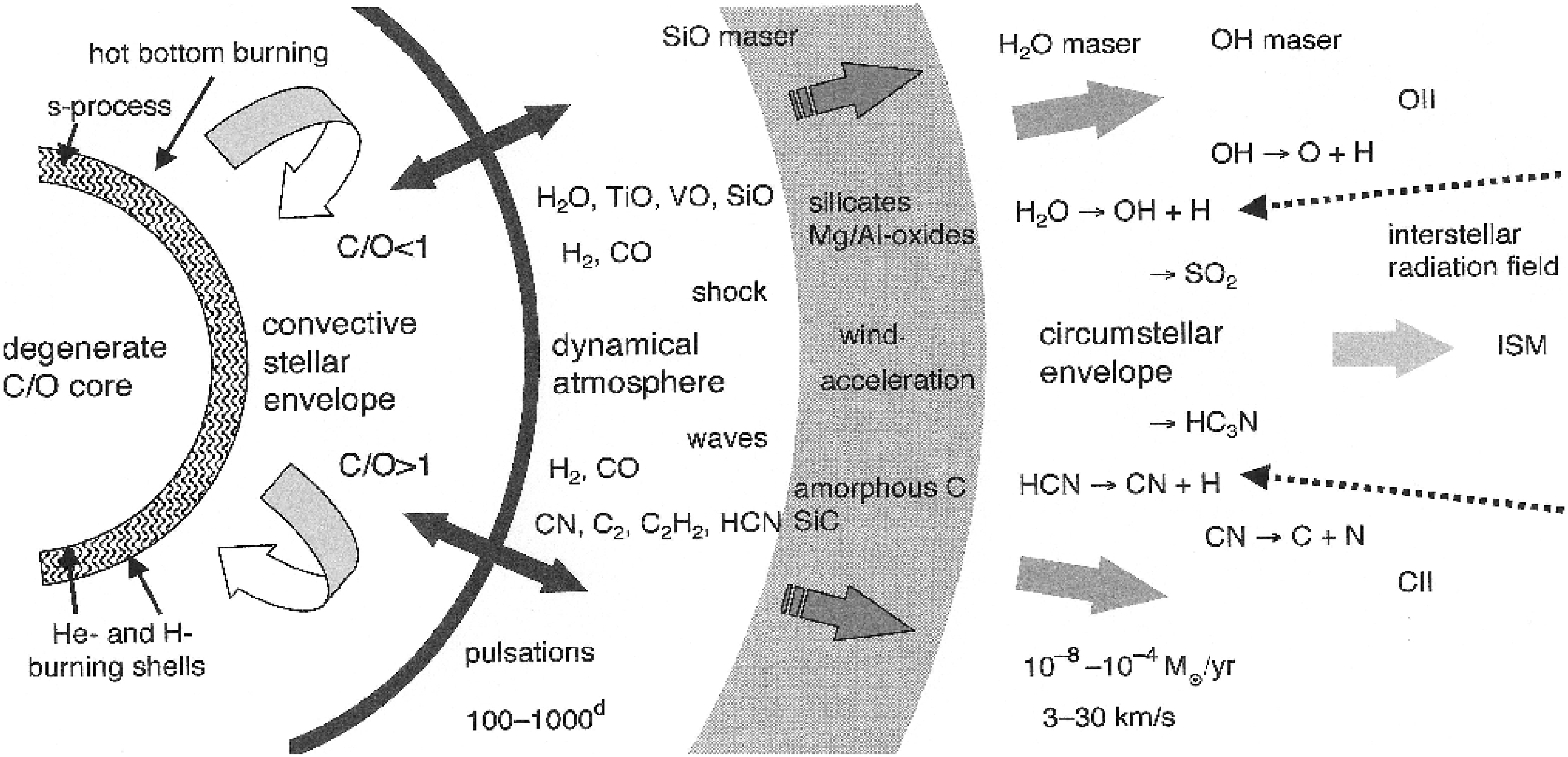
  -> Possibilities:
  - ~~Interstellar gas measurements~~
  - (Presolar grains)
  - **Dense outer layers of stellar atmosphere:** Obscured by wind (little to no information), only possible for low mass-loss rates (incomplete sample)

Observations

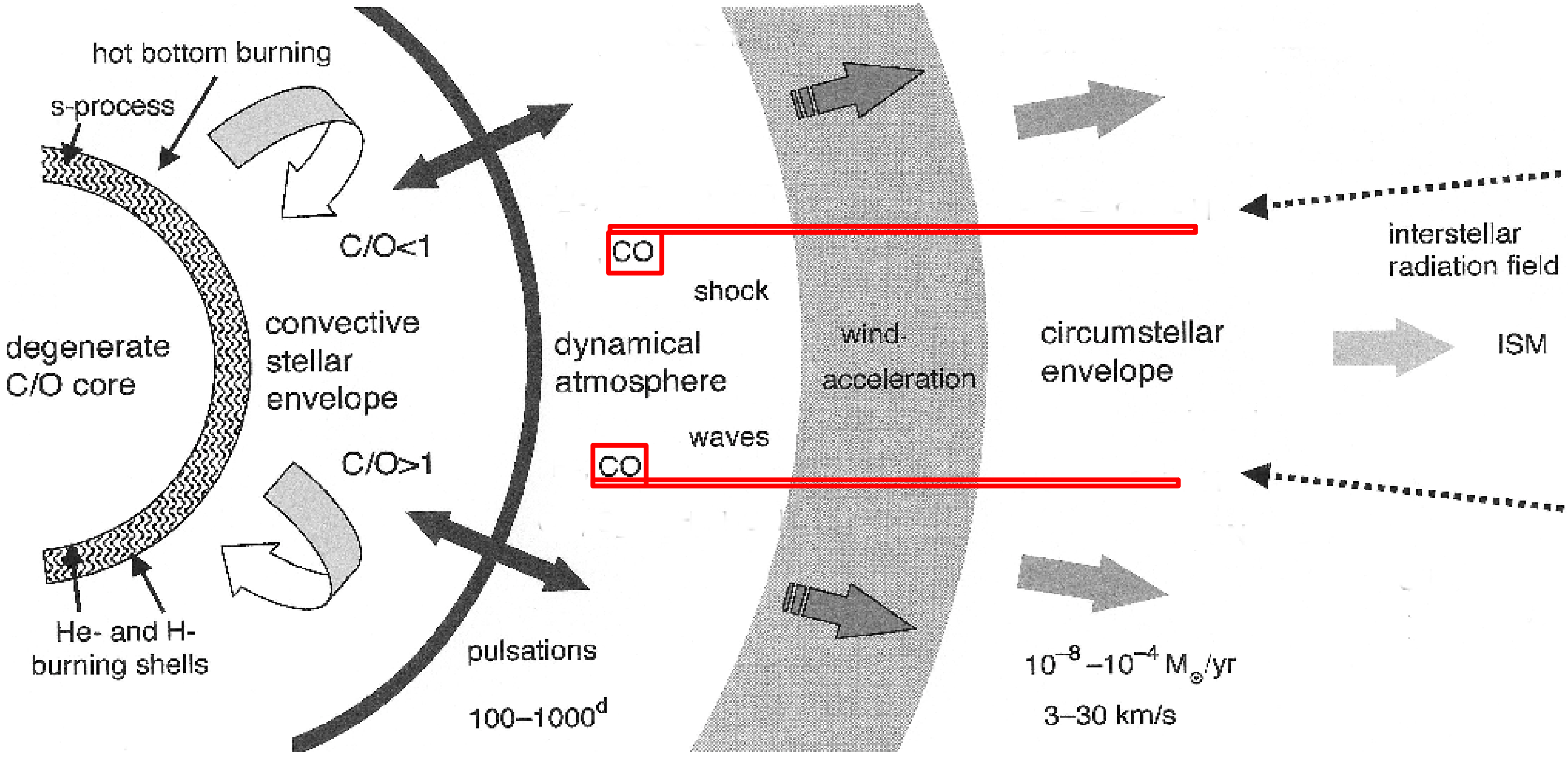
- Study effect of nucleosynthesis and DUs by means of isotopic ratios
  -> Possibilities:
  - ~~Interstellar gas measurements~~
  - (Presolar grains)
  - (Dense outer layers of stellar atmosphere)
  - **Teneous extended CSE**
    (best effort so far: Kahane et al. 1992
    → **5**(4)! C-rich envelopes)

AGB extended CSE



Adapted from
Habing & Olofsson, 2003

AGB extended CSE



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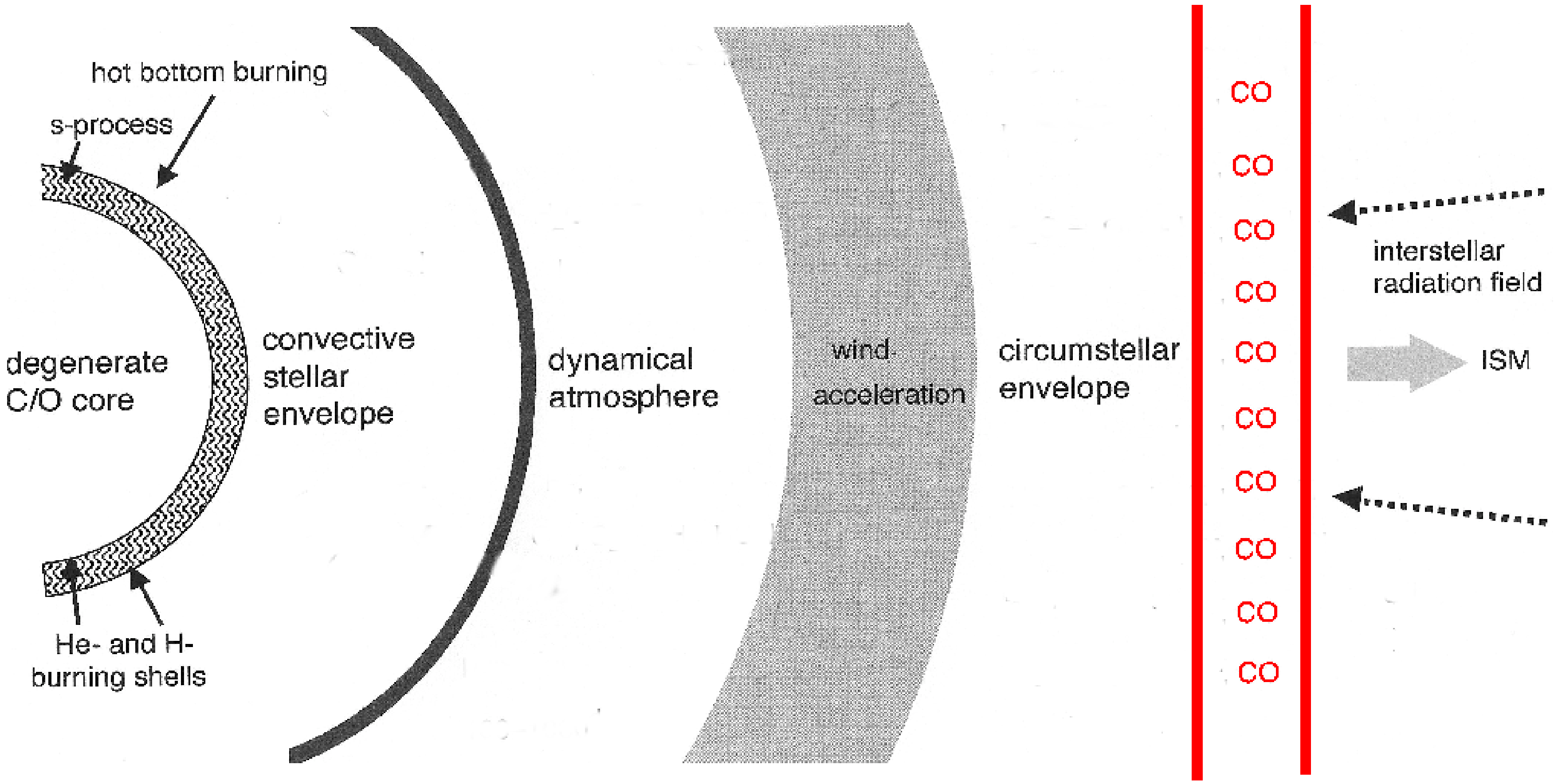
AGB extended CSE



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Carbon monoxide

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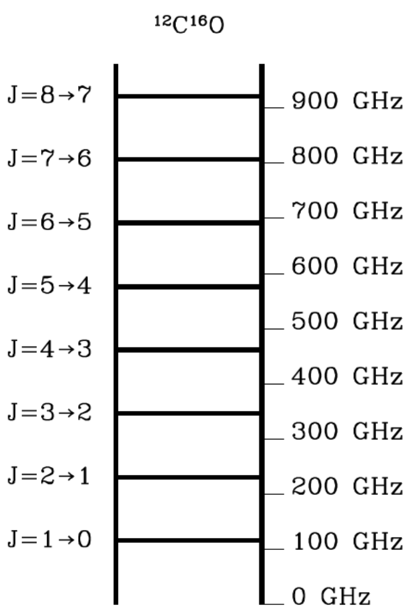
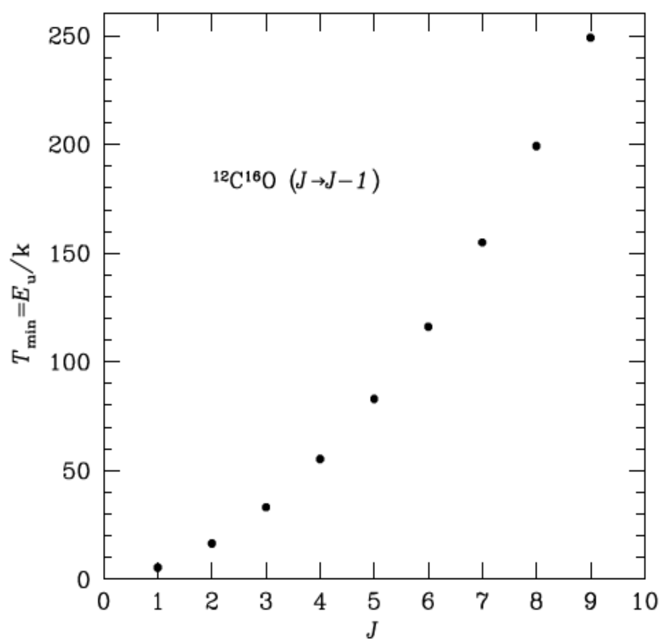
- Highly abundant (both in C- as M-type stars)
- Exceptionally stable:
  non-reactive to dust and not easily photodissociated
- Easily interpreted spectrum:





Long wavelength astronomy

- IRAM 30m (Pico Veleta)

  80 -370 GHz

  J = 1->0
  J = 2->1
  J = 3->2

  HPBW: 2460 / f [GHz]

Photo courtesy of Institut de RadioAstronomie Millimétrique

Long wavelength astronomy

- APEX Atacama Pathfinder EXperiment (12m)

  210 -500 GHz

  J = 2->1
  J = 3->2
  J = 4->3

  HPBW: 6240 / f [GHz]

Photo courtesy of Atacama Pathfinder EXperiment

Long wavelength astronomy

- Herschel PACS/HIFI

Heterodyne Instrument
for the Far Infrared HIFI:
480 – 1250 GHz

Photometer Array Camera
and Spectrometer PACS:

1400 – 5000 GHz

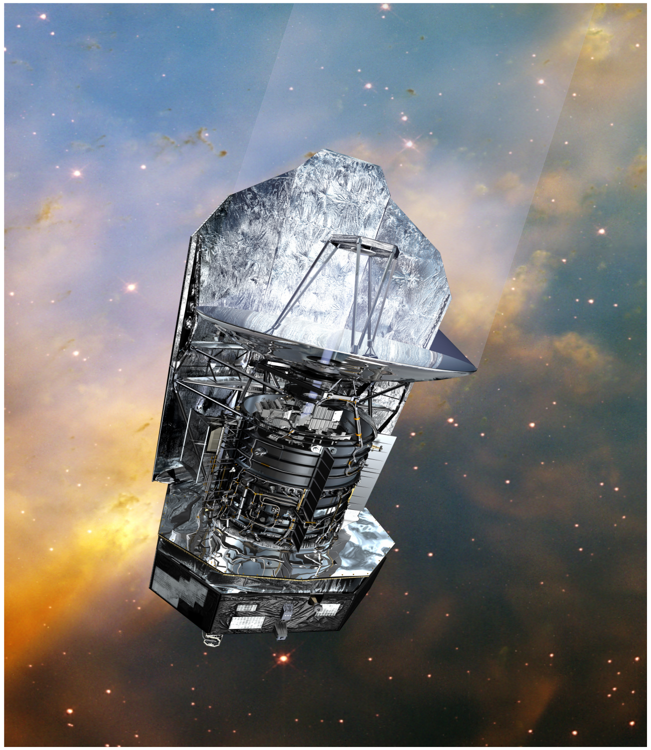


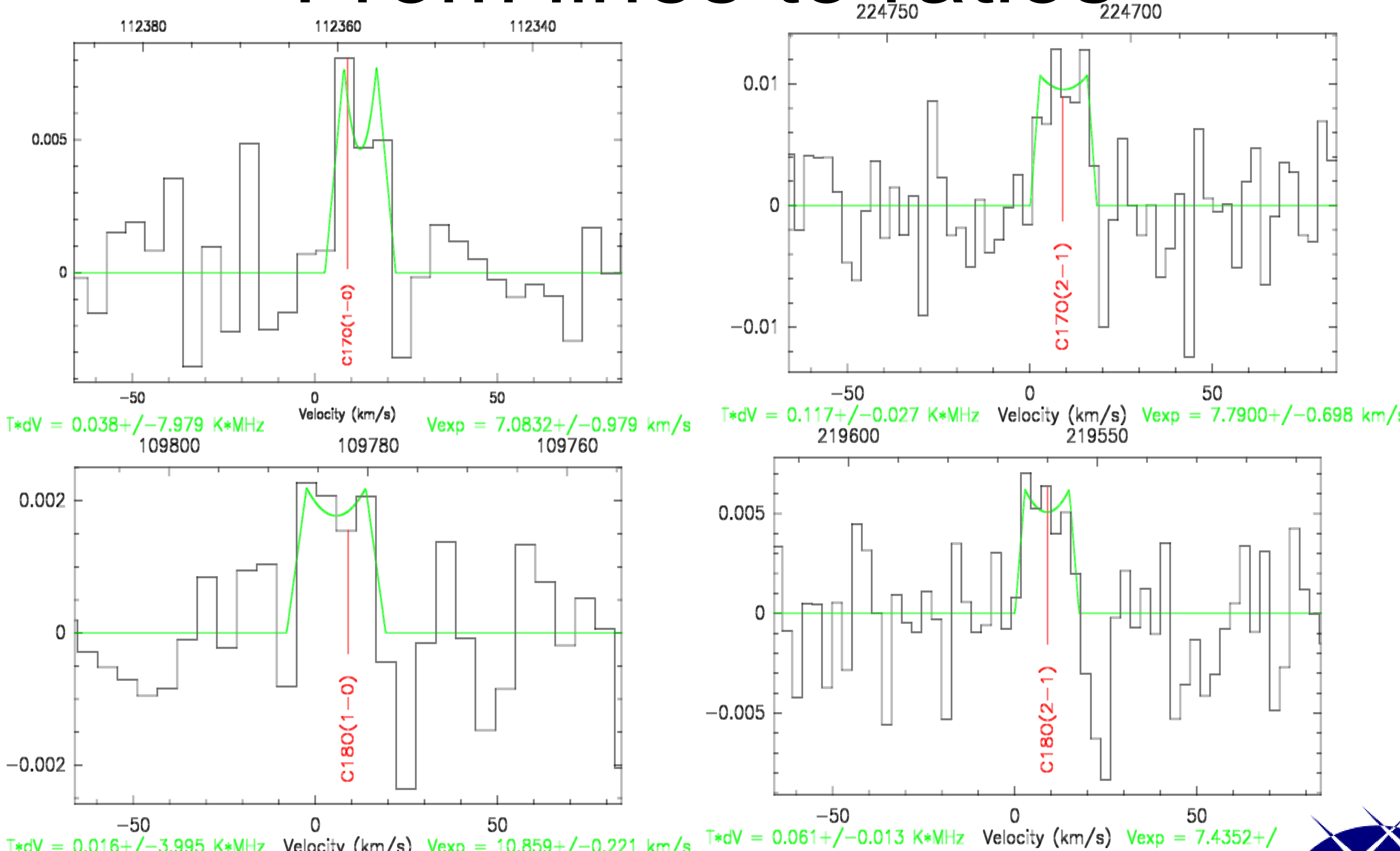
Photo courtesy of European Space Agency

Observations: Current sample

	^{13}CO (1 – 0) 110.2GHz	^{13}CO (2 – 1) 220.4GHz	$C^{17}O$ (1 – 0) 112.4GHz	$C^{17}O$ (2 – 1) 224.7GHz	$C^{18}O$ (1 – 0) 109.8GHz	$C^{18}O$ (2 – 1) 219.6GHz
C-stars						
AFGL 3068	X	X	/	X	X	X
CW Leo	X	X	X	X	X	X
II Lup		X		/		/
LP And	X	X	X	X	(X)	X
R Lep		X		/		/
RV Aqr		X		/		/
RW LMi	X	X	X	X	/	X
U Hya		X		/		/
V384 Per	X	X	X	X	/	X
Y CVn	X	X	/	/	/	/
M-stars						
GX Mon	X	X	(X)	X	(X)	X
IK Tau		X		/		X
IRC+10365	X	X	/	/	/	X
IRC+50137	X	X	/	/	X	X
IRC+60169	X	X	(/)	/	(/)	(/)
IRC-30398		X				/
R Aql		X		/		/
R Cas	X	X	(/)	/	/	(/)
R Dor		X		/		/
RT Vir		X		/		/
RX Boo	X	X	/	(/)	/	/
W Hya		X		/		/
WX Psc	X	X	/	X	X	X
S-stars						
W Aql		X		/		X
χ Cyg	X	X	X	X	X	X

- ~220 h observing time
- 8 sources for which we can already perform a $^{17}O/^{18}O$ study (5 C, **2 M**, **1 S**)
- +1 APEX run ongoing
  +1 APEX run starting next period

From lines to ratios



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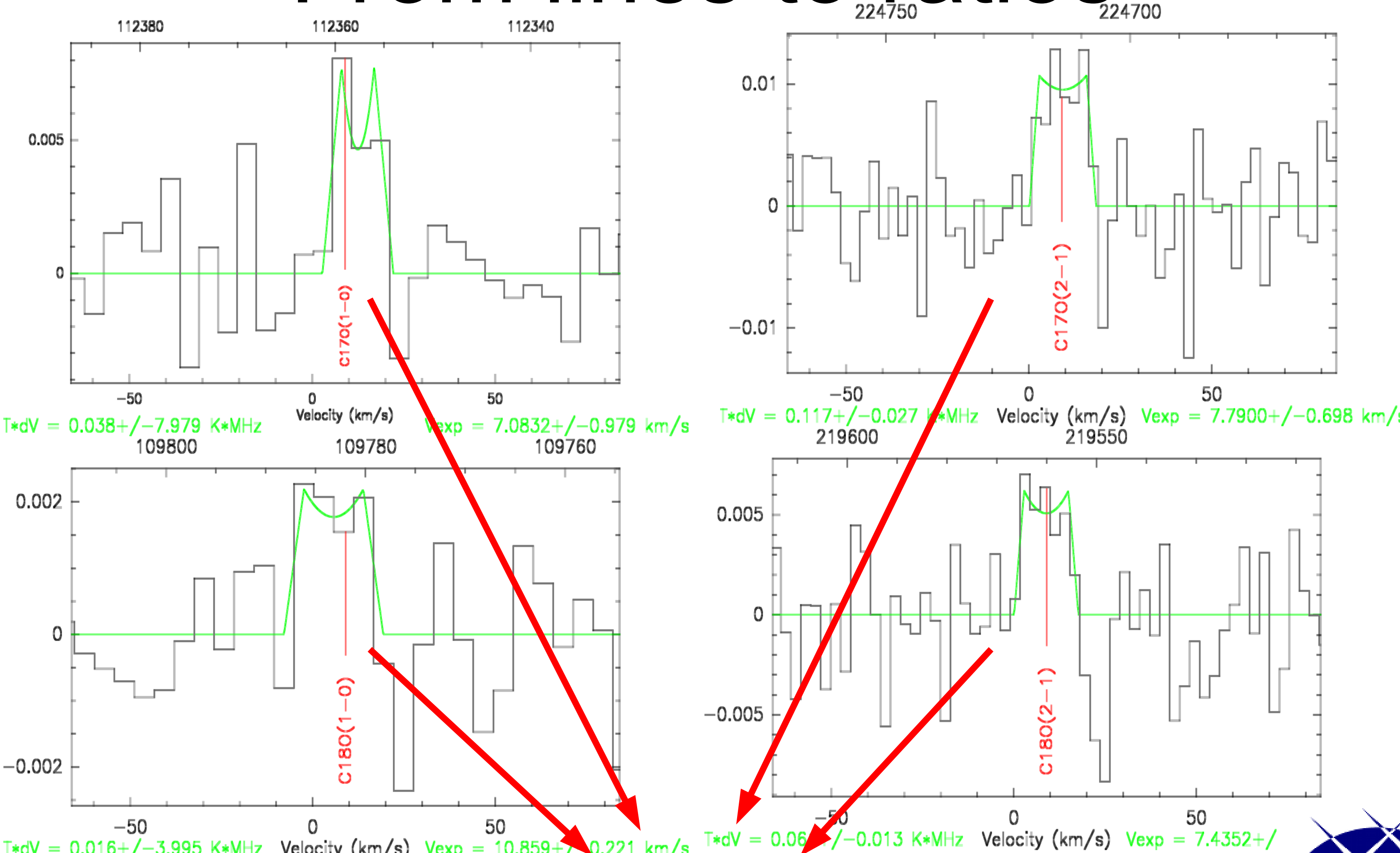

$^{17}O/^{18}O$

From lines to ratios

$I(C^{17}O)/I(C^{18}O)$ corr. for Einstein A ($\sim\nu^{-2}$)

↓

$(C^{17}O)/(C^{18}O)$

- Frequencies relatively close

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- Frequencies relatively close ✓
- Line excitation mainly collisional

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↓

$(C^{17}O)/(C^{18}O)$

- Frequencies relatively close ✓
- Line excitation mainly collisional ✓ (for low J)
- Optically thin
- Same line forming regions

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$(C^{17}O)/(C^{18}O)$

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- Optically thin
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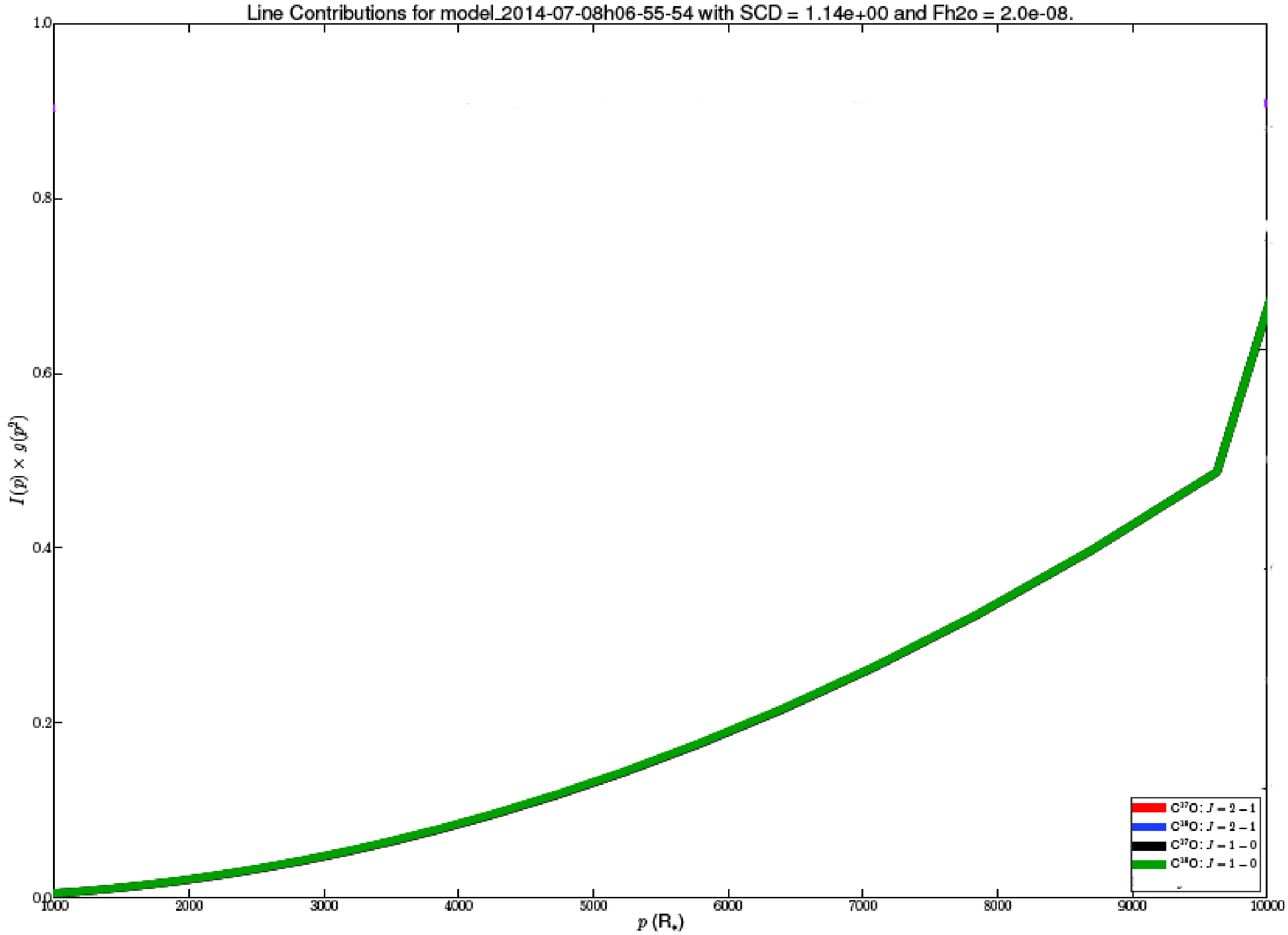
} readily checked With non-LTE radiative transfer code (GASTRoNOOm: Decin et al. 2006)

Line forming regions



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$I(C^{17}O)/I(C^{18}O)$ corr. for Einstein A ($\sim\nu^{-2}$)

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$(C^{17}O)/(C^{18}O)$

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From lines to ratios

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$(^{17}O)/(^{18}O)$

- Chemical fractionation
  vs.
  Selective photodissociation

From lines to ratios

$(C^{17}O)/(C^{18}O)$

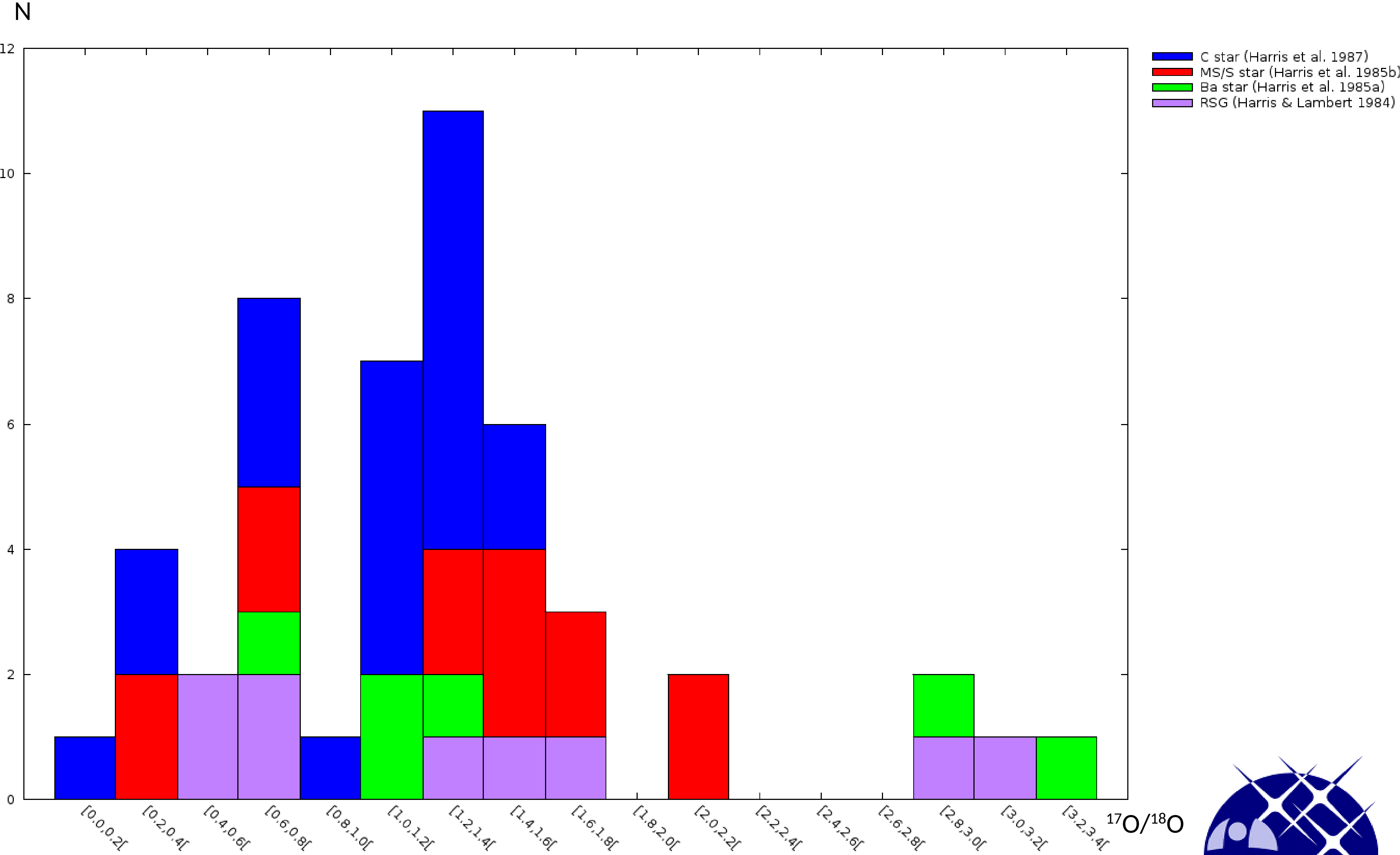
↓

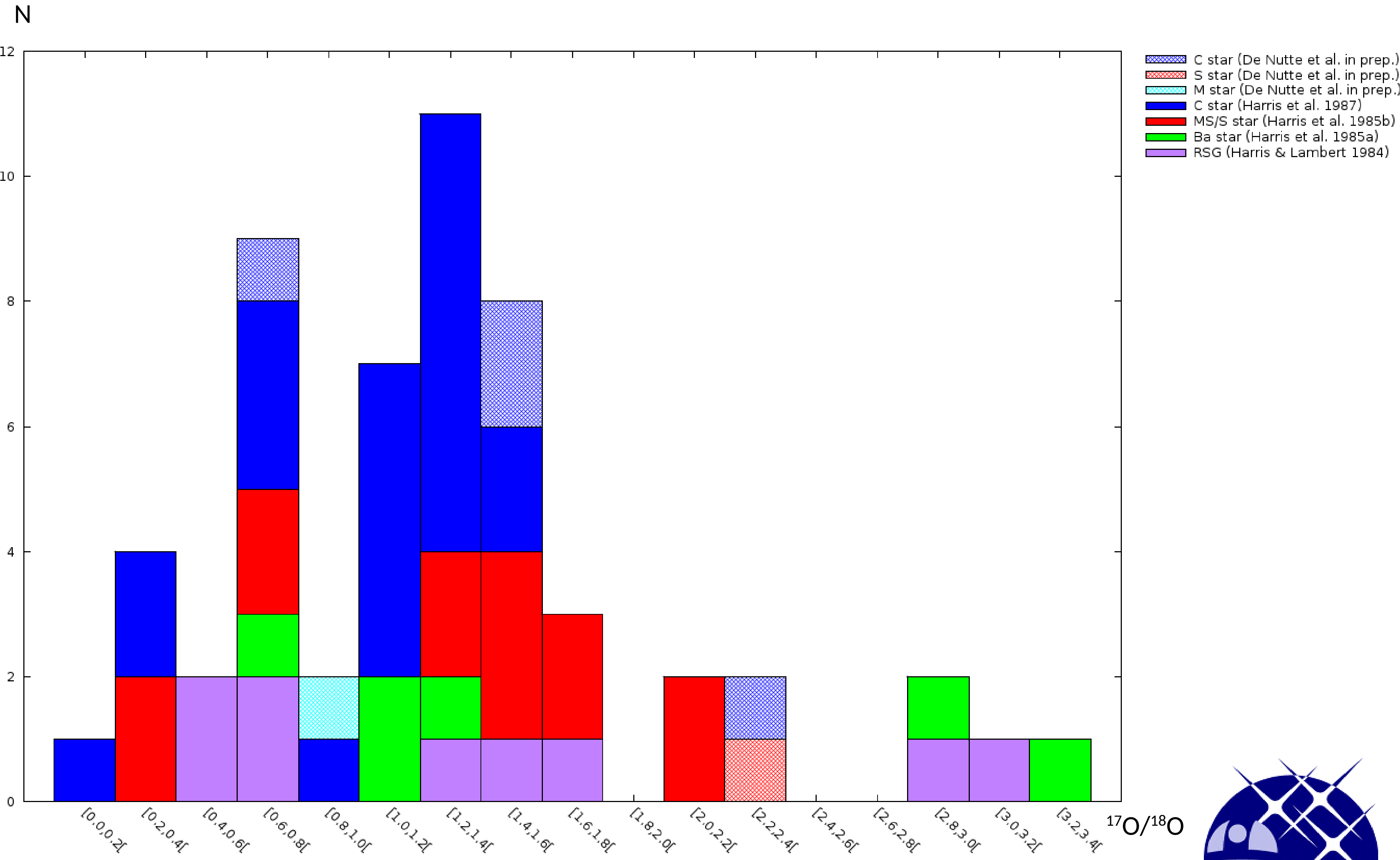
$(^{17}O)/(^{18}O)$

- Chemical fractionation
  vs.
  Selective photodissociation ✓ (See e.g. Mamon et al. 1988)

Results

Isotopic abundances


N
12
10
8
6
4
2
0
C star (Harris et al. 1987)
MS/S star (Harris et al. 1985b)
Ba star (Harris et al. 1985a)
RSG (Harris & Lambert 1984)
[0.0,0.2[
[0.2,0.4[
[0.4,0.6[
[0.6,0.8[
[0.8,1.0[
[1.0,1.2[
[1.2,1.4[
[1.4,1.6[
[1.6,1.8[
[1.8,2.0[
[2.0,2.2[
[2.2,2.4[
[2.4,2.6[
[2.6,2.8[
[2.8,3.0[
[3.0,3.2[
[3.2,3.4[
$^{17}O/^{18}O$


N
0
2
4
6
8
10
12
C star (De Nutte et al. in prep.)
S star (De Nutte et al. in prep.)
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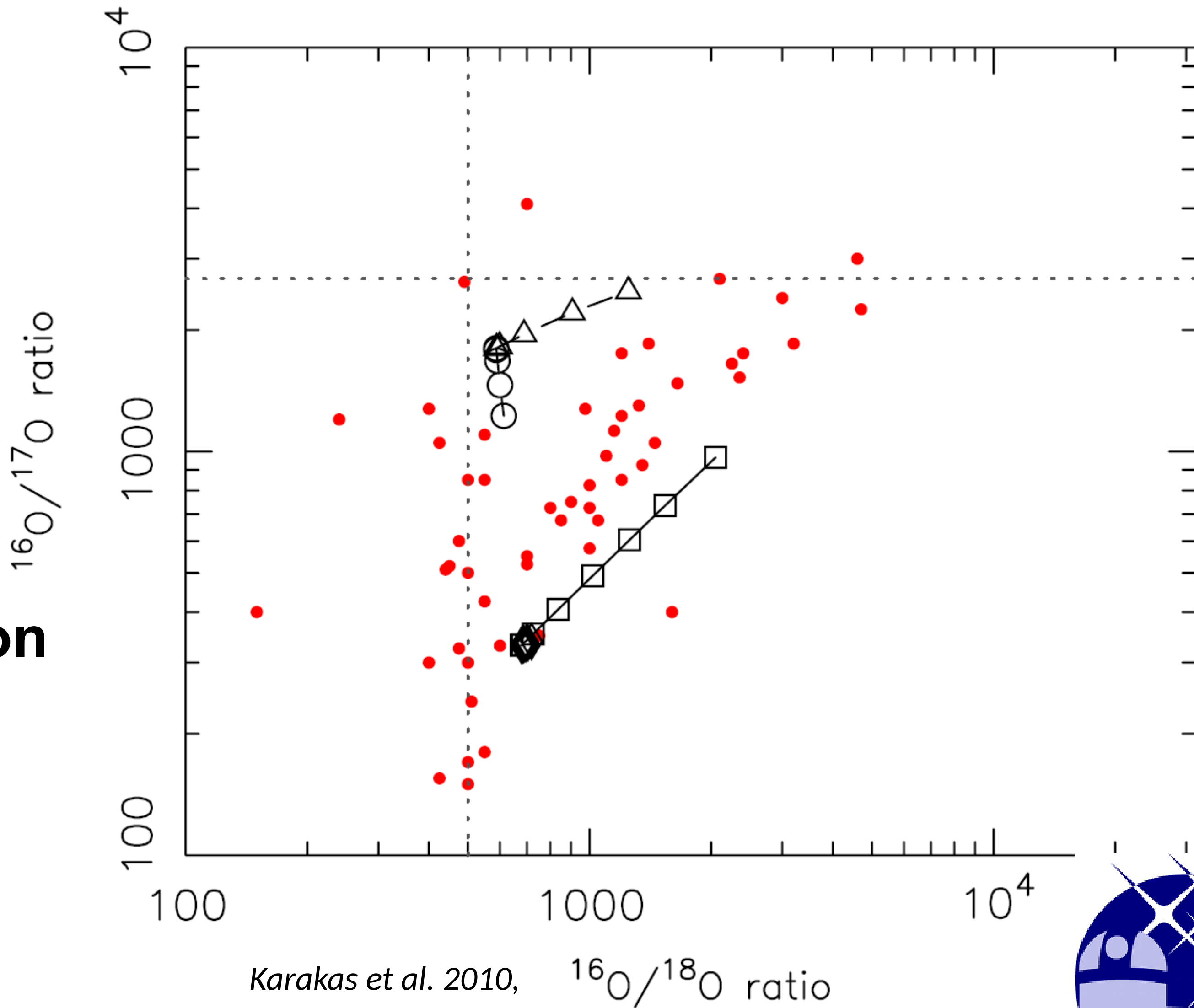
[2.8,3.0[
[3.0,3.2[
[3.2,3.4[
$^{17}O/^{18}O$

Link with stellar evolution

Combine with $^{12}C/^{13}C$ (Ramstedt & Olofsson 2014)

↓

Confront with stellar evolution models (FRANEC code Cristallo et al. 2009)



Karakas et al. 2010, ApJ 713, 374

Concluding remarks and future work

Conclusions

Conclusions

- Oxygen isotopes = excellent tracers for the efficiency of nucleosynthetic and DU processes
- CSE observations most probably best option
- Extremely weak lines make getting an adequate sample a long and tedious process
- Quick and easy line ratio study possible,
  BUT need full non-LTE radiative transfer combined with high-J lines for definitive results

Future work

- Increase sample size
- Combine with $^{12}C/^{13}C$ (Ramstedt & Olofsson 2014)
- Full non-LTE radiative transfer +PACS/HIFI (GASTRoNOoM Decin et al. 2006)
- Beyond IRC+10216
  → **ALMA**

Comic Sans References

- Boothroyd et al. 1999, ApJ 510, 232
- Busso et al. 2010, ApJ 717, L47
- Charbonnel & Lagarde 2010, A&A 522, A10
- Cristallo et al. 2009, ApJ 696, 797
- Decin et al. 2006, A&A 456, 549
- Decin 2010c, Nature, 467, 64
- Duari et al. 1999, A&A 341, L47
- Gaidos et al. 2009, ApJ 705, L163
- Glassgold 1996, ARA&A 34, 241
- Harris & Lambert 1984, ApJ 285, 674
- Harris & Lambert 1985, ApJ 299, 375
- Harris et al. 1987, ApJ 316, 294
- Kahane et al. 1992, A&A 256, 235
- Kahane et al. 2000, A&A 357, 669
- Karakas et al. 2010, ApJ 713, 374
- Maeder 1992, A&A 264, 105
- Mamon et al. 1988, ApJ 328, 797
- Nittler et al. 1997, NuPhA 621, 113
- Nittler et al. 2003, E&PSL 209, 259
- Nittler et al. 2009, PASA 26, 271
- Smith & Lambert 1986, ApJ 311, 853